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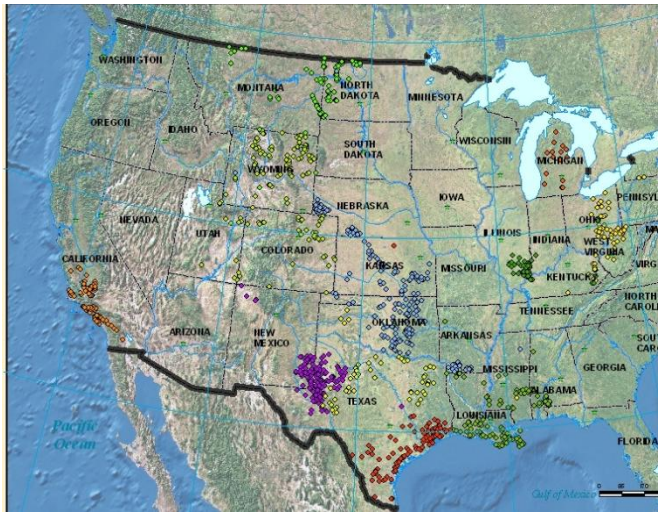

A National Resource Assessment: the Opportunity for CO2 Enhanced Oil Recovery in the United States

Phil DiPietro

Director, Situational Analysis and Benefits Division, Office of Systems, Analyses and Planning (OSAP), National Energy Technology Laboratory

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U.S. DEPARTMENT OF ENERGY

- I am visiting you from the National Energy Technology Laboratory within the United States Department of Energy on the kind invitation of Dr. Wang Daofu

- My colleagues and I have conducted an assessment of the opportunity for carbon dioxide enhanced oil recovery (CO_2 EOR) in the United States.

- I will tell you about the study, what we discovered, and lessons learned.

Acknowledgements

- This work was performed by the United States Department of Energy's National Energy Technology Laboratory in collaboration with Advanced Resources International (ARI)

- Under contract to NETL, ARI brought their "Large Oil Fields Database" to bear on the task. ARI also exercised and refined the PROPHET model to perform the reservoir simulations

- Collaborators include Vello Kuuskraa, George Koperna, Robert Ferguson, and Tyler Van Leeuwen from ARI and Don Remson and Bob Dilmore from NETL

Purpose of the CO_2 EOR Assessment

- Quantify the amount of crude oil that could be produced in the United States with CO_2 EOR
- Quantify the amount of CO_2 that could be sequestered as a result
- Estimate the impacts of advanced technologies and field practices

Value of a National CO_2 EOR Assessment

- Policy makers can see the role that CO_2 EOR could play in national priorities
  - (1) reduced GHG emissions
  - (2) reduced crude oil imports
- Businessmen can see the potential size of the market and the motivation for developing capability
- Research and development managers can see areas of technology that can influence CO_2 EOR

Analysis Summary

447 Bbbls * 68% * 20% * 56% = 34 Bbbls

447 Bbbls – original oil in place for the 6,000+ reservoirs in our database (represents 75% of total U.S. resource)

68% percent of resource screened as favorable to CO_2 EOR

20% average incremental recovery from CO_2 EOR as a percent of OOIP (stream tube model, WAG, 1.0 pore volume injection)

56% portion of technically recoverable resource that is economic at $70/bbl and 45 $/mt$CO_2$ stored

34 Bbbls – CO_2 EOR opportunity for United States

Field Properties Database

- Developed by Advanced Resources International
  - Information on over 6,000 reservoirs
  - Data gathered from over 30 years of analysis projects
- Types of information

Field Name	Depth
Reservoir Name	Thickness
Location (Latitude/Longitude)	Oil Gravity/Viscosity
Original Oil in Place (OOIP)	Pressure (Original & Current)
Estimated Ultimate Recovery (EUR)	Temperature
Remaining Oil Resource	Permeability
Lithology	Porosity
	Fluid Saturations (Oil, water)
	Dykstra-Parsons

Screening Criteria

Field minimum size	50 million bbls OOIP
Reservoir minimum depth	3,000 feet
Crude oil minimum gravity	17.5 API

Porosity not a screening criteria

Sandstone/carbonate not a screening criteria

4,879 reservoirs out of 6,354 eliminated from further consideration

Remaining 1,655 fields represent 68% of OOIP

CO_2 Prophet CO_2-EOR Screening Model

- Initially developed by Texaco in 1986 under a DOE collaboration
- Defines streamtubes to describe fluid flow between injection and production wells
- Performs oil displacement and recovery calculations along the streamtubes using finite difference routine
- Mixing parameters specify fluid mixing/viscous fingering behavior
- Key model inputs:
  - Fluid properties
  - Reservoir properties
  - Relative permeability parameters
  - Flood pattern configuration
  - CO_2 and water injection scenario
  - Miscible or Immiscible
- Available at: http://www.netl.gov.doe/technologies/oil-gas/software/
- Advanced Resources International has enhanced the model

Miscibility determination

- Assume reservoir pressure gradient 0.6 psi/ft
- Minimum Miscibility Pressure (MMP) derived from crude oil API gravity
  - **Cronquist: MMP = 15.988*T $^{(0.744206+0.0011038*MWC5+)}$**
  - **Mungan: MW C_5+ = 4248 * (API)$^{-0.87}$**
  - T is current reservoir temperature
  - MW C_5+ is the molecular weight of pentanes & heavier fractions of the oil
  - Impurities not included in the Cronquist exponent (H_2S, N_2, CH_4)
  - recent work by Yuan, Johns, Egwenu, et.al., showed the Cronquist correlation provided the best match

Current Best Practice CO_2 Flood Scenario

- 1.0 pore volume CO_2 injection
- Tapered water-alternating-gas
- 5 spot pattern (1:1 injection to producer well ratio)
- Pattern acreage variable
- No water slug at the end to recover CO_2
- Fluid and reservoir properties for each field taken from the database, expertise used to fill gaps in the data
  - Analogs from similar fields
  - Estimates based on well performance during primary and secondary production

Economic Analysis

- Spreadsheet-based cash flow model calculates the rate of return on an investment in a CO2 flood at a given reservoir
- PROPHET model results provide:
  - Annual CO_2 purchases, CO2 recycle rate, and crude oil flows
- Heuristics, judgment are used to estimate:
  - Capital cost of drilling and re-working wells
  - Electricity requirements for recompression, water injection, etc.
  - Royalty and ad valorem taxes
  - Other operating charges
- If the rate of return on capital is greater than 15%, the reservoir is considered economically recoverable
- Fields representing 56% of technically recoverable resource pass the rate of return benchmark

Analysis Summary (recap)

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34 Bbbls – CO_2 EOR opportunity for United States

* stream tube model, WAG, 1.0 pore volume injection

Optimistic Estimate

- Redo PROPHET model runs for each reservoir with inputs adjusted to characterize an advanced technology case
  - Longer CO_2 injection (1.5 pore volume)
  - Mobility ratio enhancers (water viscosity 3 cps)
  - Increased recovery from poorly swept zones within reservoirs
- Increase CO_2 EOR economically recoverable resource by 74%, from 34 to 59 billion barrels

Conservative estimate

Technically Recoverable from CO_2 EOR, lower 48 states, 1.0 pore volume, Bbbls

Reservoir Evaluation Matrix		Lithology: Carbonate	Lithology: Sandstone
Geologic Complexity	Low Complexity	12.5	14.3
Geologic Complexity	HIgh Complexity	10.0	10.6

- Remove Alaska
- Remove off-shore Gulf of Mexico
- Remove reservoirs that have combined primary and secondary recovery under 32% OOIP - a proxy for difficulty in recovering the remaining oil
- Technically recoverable CO_2 EOR opportunity is reduced to 27 billion barrels
- Apply the 56% ratio to estimate 15 billion barrels economically recoverable

Environmental Assessment

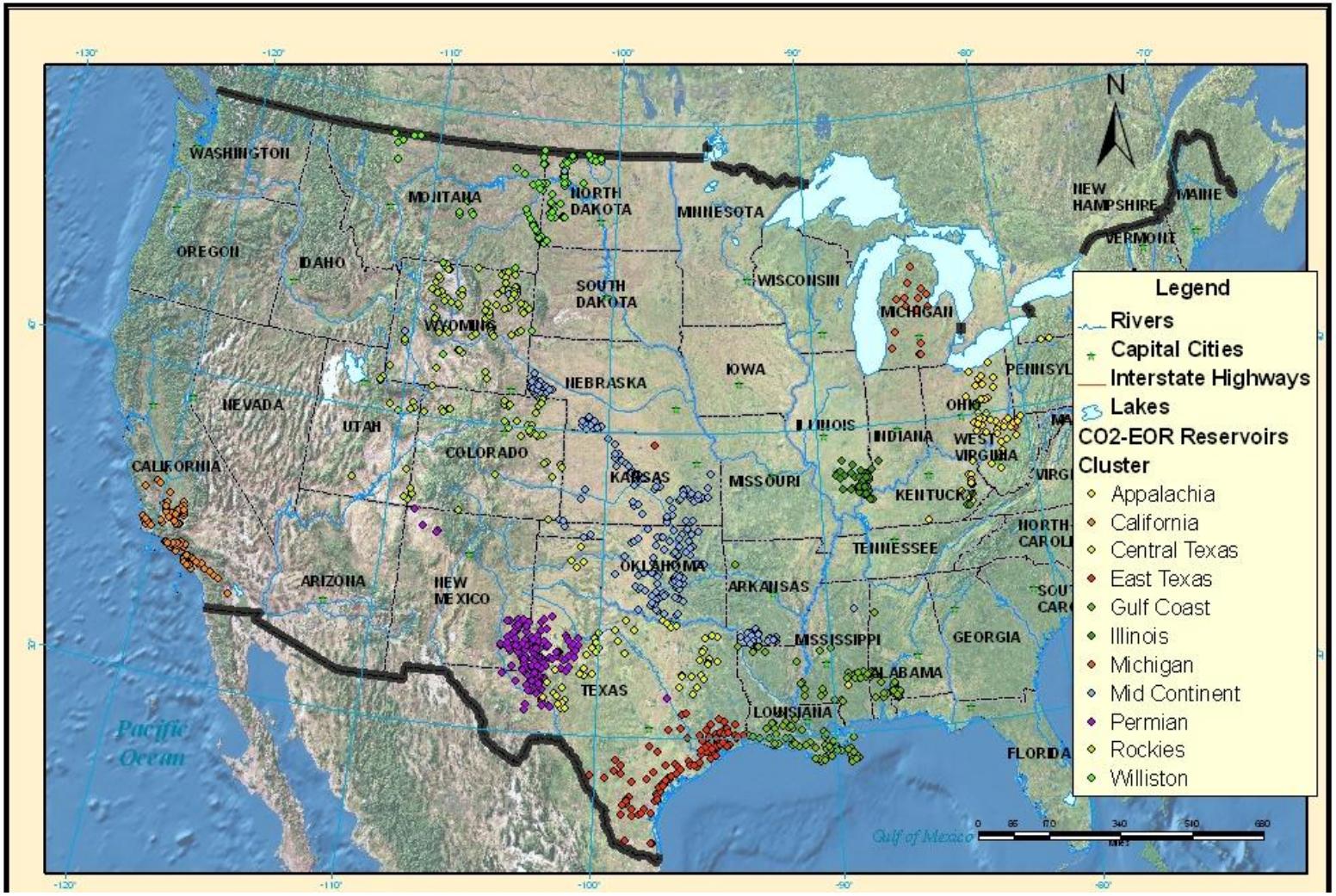
- Compared to primary and secondary recovery, CO_2 EOR requires a large amount of energy per barrel of crude oil produced
- NETL has performed a life cycle analysis of a CO_2 EOR flood
- We have found that a 1.0 pore volume flood consumes 0.14 btus of energy per btu of crude oil produced
  - Compression of recovered CO_2
  - Injection pump for produced brine
  - Tank Battery, processing of produced hydrocarbon/water
- The resulting upstream GHG emissions are 77 kg$CO2_e$ per barrel
  - Includes upstream emissions from power consumed at the EOR facility (37%)
  - Does not include GHG emissions from capturing CO2

The high technology CO_2 EOR scenario produces more oil, uses more energy

	CO_2 EOR scenario	
Hydrocarbon Pore Volume CO_2 Injected	1.0	1.5
U.S. Economically Recoverable Oil (Billion barrels)	34	59
CO_2 storage from EOR (Billion mt CO_2)	9.0	12.0
CO_2 sequestration (Mscf/bbl)	4.9	3.8
Duration of single flood (years)*	19	28
Energy use (btu consumed per btu oil equivalent produced)*	0.14	0.21
CO_2 emissions (kg CO_2e/bbl crude oil)	77	109

*** Estimated from streamtube modeling of average Permian Basin reservoir with tapered WAG injection in a 40 acre 5 spot pattern, CO_2 injection rate of 0.25 MMscf/day, water injection rate of 500 bbl/day**

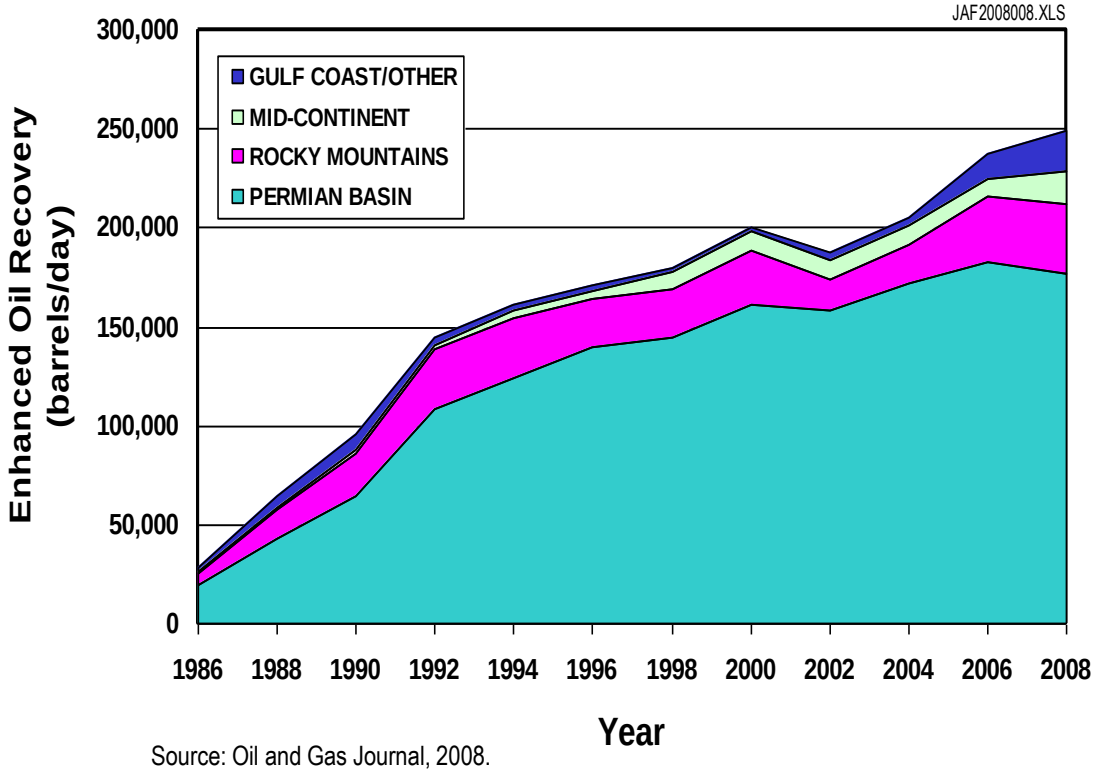
Field level assessment enables regional analysis and systems planning



Basin-level Data

Basin/Area	Total in Database		Favorable to CO_2 EOR		CO_2 EOR Prodn., % OOIP (1.0 PV)	CO_2 EOR technical opportunity (database), Bbbls	Scale up to account for all fields	CO_2 EOR technical opportunity (national), Bbbls
	#	OOIP (Bbbls)	#	OOIP (Bbbls)				
1. Alaska	45	50.7	33	42.5	20%	8.6	1.0	8.6
2. California	187	75.2	86	31.6	18%	5.7	1.1	6.3
3. Gulf Coast	298	26.4	155	20.2	21%	4.2	1.7	7.0
4. Mid-Continent	246	53.1	102	28.0	23%	6.4	1.7	10.7
5. Illinois/Michigan	172	12.0	72	4.6	17%	0.8	1.5	1.2
6. Permian	228	72.4	190	63.1	21%	13.5	1.3	17.8
7. Rockies	187	23.7	92	18.0	16%	2.9	1.4	4.2
8. Texas, East/Central	213	67.4	161	52.4	21%	10.9	1.6	17.6
9. Williston	95	9.4	54	7.2	25%	1.8	1.6	2.5
10. Louisiana Offshore	4,495	46.1	642	29.6	20%	5.8	1.0	5.8
11. Appalachia	188	10.6	68	7.4	16%	1.2	1.3	1.6
Total	**6,354**	**447.0**	**1,655**	**304.6**	**20%**	**61.8**	**1.34**	**83.3**

Growth of CO_2-EOR Production in the U.S.



Source: Oil and Gas Journal, 2008.

Current CO_2 EOR production is 0.25 MM bbls/day

The mid level estimate for CO_2 EOR economically recoverable resource is 34 B bbls

34 B bbls produced over 50 years is equivalent to ~2 MM bbls/day – an 8 fold increase over the current level

Next Steps

- History match and refine the PROPHET model
- Explore the opportunity for CO_2 injection in residual oil zones
- Publish a life cycle emissions analysis of different CO_2 EOR operational scenarios

Summary

- The middle estimate for the CO_2 EOR opportunity in the United States is 34 billion barrels of oil (economically recoverable)
  - Optimistic estimate 59 B bbls
  - Conservative estimate 15 B bbls
- That much CO_2 EOR could provide storage of 7-12 B mt CO_2
- A 1.0 pore volume CO_2 flood consumes 0.14 btus of energy for each btu of crude oil produced, emits 77 kg CO_2 per bbl of oil

Thank you!